Space-based CR experiments: Results and perspectives

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CR spectrum: the overall picture

Space = Direct CR measurements*

Key points:
- HEP techniques
- Particle Identification
- Good calibration of energy scale
- Mass/size constraints limits

The everlasting challenge: collection factor ($m^2\text{sr yr}$) increase...

* with some noticeable exceptions: as the EUSO concept!
Space Based measurements

**Chemical composition**

- Solar wind particles
- Solar energetic particles
- Cosmic Rays

**The electron component**

**Sources**

- ISM

**Propagation**

**New Physics?**

**Earth & Sun**

**Anti-matter**
Stratospheric Balloons: from few hrs to months

Magnetic Spectrometers

- BESS/POLAR/TEV (9 Flights)
- WIZARD (6 Flights)
- HEAT/PBAR (4 Flights)

Calorimetry, TRD +

- RUNJOB (62 day, 10 Flights)
- TRACER (18 days, 3 Flights)
- CREAM (161 days, 6 Flights)
- ATIC (53 days, 3 Flights)
- TIGER/S-TIGER (2/55 days)

IMAX92, BESS-TEV, BESS93-95-97-98-99-00, AESOP94-97-98-00-02-, CAPRICE94, HEAT95, RICH97, ISOMAX98..

JACEE, BESS-Polar/II, ATIC201-02-03, TRACER2003, CREAM-I, CREAMII, TIGER, SUPER-TIGER

BETS97-98

Lynn Lake

Palestine

Fort Summer

Kamchatka

Syowa

McMurdo

BETS2004

Kiruna

RUNJOB
Space:

**Long missions (years)**
- Small payloads
- Low energies

**IMP series** $< \text{GeV/n}$
**ACE-CRIS/SIS** $E_{\text{kin}} < \text{GeV/n}$
**VOYAGER-HET/CRS** $< 100 \text{ MeV/n}$
**ULYSSES-HET** (nuclei) $< 100 \text{ MeV/n}$
**ULYSSES-KET** (electrons) $< 10 \text{ GeV}$
**CRRES/ONR** (nuclei) $600 \text{ MeV/n}$
**HEAO3-C2** (nuclei) $< 40 \text{ GeV/n}$

**Short missions (days)/ Larger payloads**
- **CRN on Challenger** (3.5 days 1985)
- **AMS-01 on Discovery** (8 days, 1998)

**Fermi-LAT**
**PAMELA**
**DAMPE**
**AMS-02**
**CALET**
Anti-matter?
Primordial anti-matter
DM indirect searches

Z>1
positrons (and electrons)
anti-protons
Balloon borne Experiment with Superconducting Spectrometer
BESS: 9 flights between 1993 and 2004

- large solenoidal thin-wall superconducting magnet: 0.3 m²sr, 0.8 T
- a time-of-flight system of scintillation counter hodoscopes
- inner drift chambers (IDC)
- a jet-type drift particle-tracking chamber
- outer drift chambers / aerogel Cherenkov counter depending on the configuration
Alpha Magnetic Spectrometer on STS-91 AMS-01 (1998)
Payload for Matter/Antimatter Exploration and Light nuclei Astrophysics - PAMELA

- Launched on 15th June 2006
- PAMELA in continuous data-taking mode for 10 years

• PAMELA on board of Russian satellite Resurs DK1
• Orbital parameters:
  - inclination ~70° (⇒ low energy)
  - altitude ~ 360-600 km (elliptical)
  - active life >3 years (⇒ high statistics)
The detector

**GF**: 21.5 cm² sr
**Mass**: 470 kg
**Size**: 130x70x70 cm³
**Power Budget**: 360W

**Spectrometer**
- **microstrip silicon tracking system** + permanent magnet
  - *Magnetic rigidity* \( R = \frac{pc}{Ze} \) MDR≈1(0.25) TV
  - *Charge sign*
  - *Charge value from* \( dE/dx \)

**Electromagnetic calorimeter**
- W/Si sampling (16.3 X₀, 0.6 λl)
  - Discrimination e⁺ / p, anti-p / e⁻ (shower topology)
  - Direct E measurement for e⁻

**Neutron detector**
- 36 He³ counters:
  - High-energy e/h discrimination

**Time-Of-Flight**
- plastic scintillators + PMT:
  - Trigger
  - Albedo rejection;
  - Mass identification up to 1 GeV;
  - Charge identification from \( dE/dx \).
Alpha Magnetic Spectrometer on the ISS: AMS-02

- Launched on May 16, 2011
- Installed on ISS May 19, 2011
- AMS-02 foreseen to operate for the entire ISS lifetime

Dimensions:
- 5m x 4m x 3m
- 7.5 tons
- GF ≈ 0.5 m²sr
The Charge and Energy (momentum) are measured independently by many detectors.
Anti-He/He

differential upper limit with 6.3 M He events collected in PAMELA

\[
\frac{N_{\text{He}}(R_i; R_f)}{N_{\text{He}}(R_i; R_f)} < \frac{3}{\int_{R_i}^{R_f} F(R) dR} = \frac{3}{\int_{R_i}^{R_f} \frac{dN'_{\text{He}}(R)}{dR} dR} \cdot \frac{\epsilon_{\text{He}}(R_i; R_f)}{\epsilon_{\text{He}}(R_i; R_f)}.
\]
Anti-He/He

Waiting for AMS-02 ......
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DM indirect searches

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2008-2009: the $e^+ / e^-$ puzzle

An excess of cosmic ray electrons at energies of 300–800 GeV

Vol 456 | 20 November 2008 | doi:10.1038/nature07477

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

Vol 458 | 2 April 2009 | doi:10.1038/nature07942

Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope

PRL 102, 181101 (2009)
The actual status (not the end of the story)

High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

10.9 million e+ and e- events
e+/e- fluxes

(a) Electrons

(b) Positrons

AMS-02
PAMELA
Fermi-LAT

AMS-02
PAMELA
Fermi-LAT
MASS
CAPRICE
AMS-01
HEAT

Energy [GeV]

Energy [GeV]
e+/e- fluxes

Electron Spectrum

Positron Spectrum

$E^2$ Flux [GeV$^2$/s sr m$^2$ GeV]]

Electrons

Positrons

9,200,000

600,000
**$e^+e^-$ fluxes**

![Graph showing $E^3 \times \Phi$ (GeV$^2$ [m$^2$ sr sec$^{-1}$]) versus Energy (GeV)]

- **AM$^S$-02 (2011-2013)**
- **ATIC01&02 (2001 & 2003)**
- **BETS04 (2004)**
- **BETS9798 (1997 & 1998)**
- **CAPRICE94 (1994)**
- **Fermi-LAT (2009)**
- **HEAT94 (1994)**
- **HEAT9495 (1994 & 1995)**
- **HEAT95 (1994 & 1995)**
e^+e^- fluxes @ SciNeGhe (see.18/10)

Waiting for new results from:

+ AMS
+ CALET
+ DAMPE
Anti-matter?

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anti-protons
Anti-proton/proton

the early times (1984)

...around 2000

HEAT $\approx$ 70 events
CAPRICE $\approx$ 31 events
Anti-proton/proton : 2010

BESS-POLAR (2004) ≈ 1520 event < 4.2 GeV
PAMELA (2006-2009) ≈ 1500 events
Anti-protons/proton: 2016

PRL 117, 091103 (2016) ≈ 350,000 anti-protons

[Graph showing the ratio of antiprotons to protons as a function of rigidity.]
Anti-protons/protons: 2016

PRL 117, 091103 (2016) \( \approx 350,000 \) anti-protons

![Graph showing the ratio of anti-protons to protons against rigidity and kinetic energy]
Anti-protons/proton: 2016

Energy independent above 60 GV

\[ \frac{\Phi^p}{\Phi^p} \text{ ratio} \]

\[ |\text{Rigidity}| \text{ [GV]} \]

AMS-02
PAMELA

\[ 10^{-4} \]
\[ 10^{-5} \]
The accuracy of the latest measurement challenges current knowledge of cosmic background!
The DM backgrounds & The CR physics!

- Origin, acceleration: p, He, C...
- Propagation & ISM: B/C, Li, Be/B
- Sun/Earth effects: time dependence

\[ \pi^+ \rightarrow \mu^+ \rightarrow e^\pm \]
\[ p + p \rightarrow p + p\bar{p} \ldots \]
Solar effects on CR

![Graph showing positron fraction vs. energy and antiproton/proton ratio vs. kinetic energy.]

- AMS-02
- PAMELA
- Fermi
- AMS-01
- HEAT
- TS93
- CAPRICE94

- Moskalenko et al.
- Bieber et al.
- BESS-Polar
- BESS (2000)
- BESS (95+97)
A long journey in planetary mission, (jupiter, saturn, titan), heliosphere and interstellar space...

In orbit from Sept.5 1977:
38 years ..9 months..and still counting (up to 2025...)
@ 121 a.u. out from heliospheric effects!

**Voyager-1**

&

the (un) modulated CR spectrum

Heliosphere shields 75% GCR with E>70 MeV

Mainly >70 MeV protons
From the modulated to the unmodulated spectrum...

\[ \frac{H}{He} \approx 12, \text{ flat with energy: shape not due to solar modulation but to ionization losses: V-1 is not near the source!} \]
Time dependance of the electron and positron fluxes

PRL 116, 241105 (2016)
AMS ISS Data: Jun 2011 – May 2016

2.0-2.3 GV

polarity reversal of the solar magnetic field

change rate 0.2%/month

change rate 1.7%/month

68% CL 8/2015

68% CL 11/2013
Spectral features & composition ....
Spectral features & composition

Breaks occur also at “low” energies…
AMS-02: the smooth change of spectral index

\[ \Phi = C \left( \frac{R}{45 \text{GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right] \]

AMS 2015
The proton/He flux ratio is given by $\Phi_p/\Phi_{He} = C R^\gamma$. The graph shows data from AMS-02, PAMELA, and BESS-Polar. A single power law fit is applied for $R > 45$ GV. The change of slope is marked at $\sim 45$ GV.
What about origin of spectral hardening?

Related to acceleration mechanisms at source?

- distributed acceleration by multiple sources at the origin?
- non linear DSA?
- reacceleration by weak shocks in the Galaxy?

Propagations effects?
- e.g. space and energy dependent diffusion coefficients?

Effect of nearby young CR sources?

Future promises more & more fun:
- precise data also on other primary/secondary species are coming;
  - AMS released just a small part of his data...and will continue to run as the ISS will be operational
  - DAMPE
  - CALET
  - ISS-CREAM
  - (HERD, ALADINO?)
B/C ratio 2016 (sub. PRL)

\[ \Delta = -0.333 \pm 0.014 \text{(fit)} \pm 0.005 \text{(sys)} \]
B/C ratio 2016 (AMS sub. PRL)

Expected measurements

- Proton and nuclei up to 100 TeV
- Electron Spectrum up to 10 TeV
  - Detect the possible cutoff around 1 TeV
  - Detect possible spectrum structures and anisotropies (DM signals)

AMS & Nuclei in Cosmic Rays

B/C : Li, Be, B, C, N, O.....Fe...

Isotopes ([H/H], [He/He],..)
Cosmic Ray Observatory on ISS
### CALET on ISS

**INSTRUMENT OVERVIEW**

**1 TeV electron**

**CHD** - Charge Detector (CHD)

- Charge Measurement \( Z = 1 - 40 \)

**IMC** - Imaging Calorimeter (IMC)

- Particle ID, Direction
- Total Thickness of Tungsten (\( W \)): \( 3 \ X_0 \), \( 0.1 \ \lambda \)
- Layer Number of SciFi Belts: 8 Layers \( \times 2(X,Y) \)

**TASC** - Total Absorption Calorimeter (TASC)

- Energy Measurement, Particle ID
- PWO: 20mm \( \times \) 20mm \( \times \) 320mm
- Total Depth of PWO: \( 27 \ X_0 \) (24 cm), \( 1.2 \ \lambda \)

<table>
<thead>
<tr>
<th></th>
<th><strong>CHD (Charge Detector)</strong></th>
<th><strong>IMC (Imaging Calorimeter)</strong></th>
<th><strong>TASC (Total Absorption Calorimeter)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>Charge Measurement ( (Z = 1 - 40) )</td>
<td>Arrival Direction, Particle ID</td>
<td>Energy Measurement, PID</td>
</tr>
<tr>
<td><strong>Sensor (+ Absorber)</strong></td>
<td>Plastic Scintillators: 2 layers, Unit Size: 32mm ( \times ) 10mm ( \times ) 450mm</td>
<td>Scintillating Fibers: 16 layers single readout: 1mm(^2) ( \times ) 448 mm Total thickness of Tungsten: ( 3 \ X_0 )</td>
<td>PWO logs: 12 layers, Unit size: 19mm ( \times ) 20mm ( \times ) 326mm, Total Thickness of PWO: ( 27 \ X_0 )</td>
</tr>
<tr>
<td><strong>Readout</strong></td>
<td>PMT+CSA</td>
<td>64-anode MAPMT+ ASIC</td>
<td>APD/PD+CSA, PMT+CSA (for Trigger)</td>
</tr>
</tbody>
</table>
ISS-CREAM:
launch June 1\textsuperscript{st} 2017

Conclusions & Perspectives

✓ Stratospheric balloon program is still relevant for specific measurements (GAPS for anti-d ?..)

✓ Space is giving an important contribution to direct CR measurements...
  ✓ PAMELA did a great job...
  ✓ AMS-02 is starting to release impressive results..and more will come in the next future
  ✓ CALET and DAMPE just launched...

✓ in 10 years large acceptance space based calorimetric experiments insuring good overlap with ground based (indirect) measurements (HERD?)

✓ Anti-matters matters ! A long term plan is needed (and is starting..) for a new antimatter large acceptance detector in orbit ..
China’s Space Station Program

2022
Phase-II

2018
Phase-II

Space Station
3 large modules
+ 2 m telescope
~10-year lifetime

2011
Phase-I

Space lab:
no living cabin

10 astronauts in 5 flights → space walk

2003
High Energy cosmic-Ray Detector (HERD)

- n10X acceptance than others, but weight 2.3 T ~1/3 AMS
- STK(W+SSD)
- Charge
- gamma-ray direction
- CR back scatter
- STK(W+SSD)
- 3D CAILO
e/γ/CR energy
e/p discrimination
Exposure (assuming GF=2.5m²sr)

- HERD (2.5 m²sr)
- DAMPE (0.3 m²sr)
- CALET (0.1 m²sr)
- CREAM-1 (H,He)
- CREAM-2 (C,N,O,Ne,Mg,Si,Fe)

(Depending on launch time)
Antimatter Large Acceptance Detector IN Orbit (ALADINO)

3D calorimetry (CaloCube)

HTC SC (SR2S)

Average B ≈ 0.88

Silicon Tracking (AMS, PAMELA)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter acceptance</td>
<td>$\sim 9 \text{ m}^2 \text{ sr}$</td>
</tr>
<tr>
<td>Spectrometer acceptance</td>
<td>$\sim 3 \text{ m}^2 \text{ sr}$</td>
</tr>
<tr>
<td>Spectrometer Maximum Detectable Rigidity</td>
<td>$&gt;20\text{ TV}$</td>
</tr>
<tr>
<td>Calorimeter energy resolution</td>
<td>$24% \div 35%$ (for nuclei)</td>
</tr>
<tr>
<td></td>
<td>$2%$ (for electrons and positrons)</td>
</tr>
<tr>
<td>Calorimeter e/p rejection power</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td>Time of Flight measurement resolution</td>
<td>180 ps</td>
</tr>
</tbody>
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*Table 1: main performance parameters of the ALADINO apparatus*